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OPTIMIZATION OF MOTOR/GEAR DRIVE SYSTEM FOR ELECTRIC
RPV(U) NU-TECH INDUSTRIES INC DAYTON OH M ISSACSON

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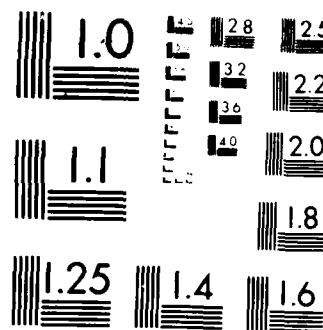
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OPTIMIZATION OF MOTOR/GEAR DRIVE SYSTEM FOR ELECTRIC RPV

Milton Isaacson

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5905 Wolf Creek Pike
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October 1986

Final Report for Period January 1986 - September 1986

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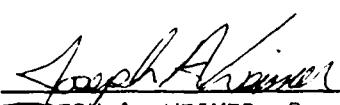
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This technical report has been reviewed and is approved for publication.


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In the bench power tests output from the motor was measured to be 5 hp. The heat rejection tests showed that adequate cooling should be attainable through further improvements in a total cooling system.

The final assembly of motor, controller and heat rejection hardware weighed only 11.6 pounds. That is much less than the 25 pound target of the original solicitation.

The feasibility of using a high speed electric propulsion system for RPV applications was proven by the success of this Phase I effort. The Phase I results show that continuation of the development effort to Phase II is justified.

High power density brushless dc motors also have significant potential for use by the government in applications other than the RPV. Specific applications include the aircraft starter/alternator, and aircraft systems such as air cooling and auxiliary power drives. Potential industrial applications include spindle power drives, fans and blowers, oil and gas well auxiliary power drives, and wind tunnel power devices.

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PROJECT SUMMARY

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PROJECT OBJECTIVES

The goal of Phase I was to prove the feasibility of electric propulsion for RPV applications by demonstrating the performance capability of a brushless dc motor with electronic controller and gear reducer system that is configured for optimum size and weight.

Specific objectives were as follow:

1. Configure an electric propulsion system for RPV application consisting of a brushless dc motor, controller, gearbox, and propeller.

The speed reducing gearbox allows use of a high speed motor, thus giving access to the inherent size, weight, and efficiency advantages of high speed brushless dc motors.

2. Design, fabricate and test a light weight, brushless dc motor and companion electronic controller to generate 5 hp and 10 hp at propeller speeds of approximately 5,000 and 6,300 rpm respectively.
3. Test the adequacy of heat rejection from the high power density brushless dc motor in the RPV configuration.
4. Package the motor, controller and heat rejection hardware for minimum size and weight.

WORK PERFORMED

Motor Development

The Motor Development effort consisted of 1) motor design and fabrication, 2) heat rejection hardware design and fabrication, and 3) component bench tests.

The following discussion is not always chronological because studies of different characteristics (e.g. heat rejection and no-load performance) and hardware (e.g. new and existing motors) were sometimes performed concurrently.

The initial motor design was chosen to be a 4 pole, 4 phase configuration. This was chosen to attain high speed operation with minimal "iron loss" (eddy current and hysteresis loss in the stator stack). The stator was constructed using 24 slot laminations because they provided the narrowest bridge ring, low cogging (for ease of starting), and a peak efficiency located near the operating point.

A preliminary performance test was run on an existing 2" long (a length specification pertains to the stack length of the stator), 4 pole motor. The test showed that a 2" long motor was too powerful for the RPV application, and that it's peak efficiency was located (on a plot of motor speed versus torque) too far to right of the required peak torque. This test implied that adequate power (torque) should be obtained from a 1" motor.

A computer analysis was made for a 1" long motor which predicted that an optimum winding design for a 4 phase, 4 pole motor would use 6 turns of #16 AWG magnet wire. A motor, designated D222 LC#1 was constructed to those conditions. Unfortunately, one phase of the stator winding was shorted to ground, and so the motor could not be run under load. The motor could however be operated as an unloaded generator.

The no-load data that was taken with the D222 LC#1 motor showed that the chosen 6 turns, #16 winding would not yield the desired no-load speed at the selected level of 200 vdc for 10 hp operation. Based upon this no-load testing, the motor winding was changed to 7 turns of #17 AWG magnet wire.

During the course of that winding change, the opportunity was taken to switch to a better stator lamination. This new lamination, which was not available at Nu-Tech at the time of the assembly of LC#1, was thinner than the first one used. This characteristic should lead to a reduction in stator "iron loss". Also, a Nomax end insulator was added to the motor to insure against another short to ground condition. The modified motor was designated D222 LC#2.

The failed stator of the D222 LC#1 motor was later used in a rig to test for motor heat rejection. Two designs of a finned motor case were constructed. The designs were designated 4-072 (having 26 fins and weighing 2.43 pounds) and 4-073 (20 fins weighing 2.09 pounds). The stator and case were instrumented with thermocouples. Current was passed through the stator to simulate motor operation, and the temperature due to stator heat generation was recorded while air was passed over the finned housing at about 34 mph. The 4-072 case (the one chosen prior to the above testing to be used in the system testing) experienced a temperature rise of 152 degrees C at a stator heat dissipation rate of 750 watts.

Heat dissipation needs to be improved, and Nu-Tech is approaching that need in two directions. First, all motor designs are considered in terms of the potential for highest attainable efficiency. As efficiency is increased, the amount of waste heat that must be dissipated is reduced. Secondly, Nu-Tech is investigating methods that might be used to enhance the transfer of the heat from the motor assembly into the airstream.

The motors were first component tested to determine performance, especially the peak efficiency at low speed (10,000 rpm, no-load). The approach was to first maximize the efficiency at low speed, assuming that the maximum efficiencies would equally compare for different motor designs at the higher speeds.

The initial power testing, performed by pulley and string, of D222 LC#2 showed that the maximum motor efficiency for the 10,000 rpm no-load speed curve was only 64%. A number of design modifications were tried on model LC#2, including minimizing lead lengths and using high voltage, low resistance transistors. However, the testing indicated that the peak efficiency could not be significantly increased.

The motor was therefore changed to a 6 phase, 4 pole unidirectional current design. But testing of this motor, designated D222 LC#3, showed a maximum no-load motor efficiency (for the 10,000 rpm no-load speed curve) of only 67%. With these results it was suspected that an 8 pole motor was required to attain significantly higher motor efficiencies.

An existing 4 phase, 8 pole, unidirectional current motor (designated D181 LC#4) was then tested to see if peak efficiency was improved in the 8 pole configuration. The test of that motor showed a peak efficiency of 80% and a stall torque of 510 ounce-inches. That data confirmed that the 8 pole configuration could improve the peak efficiency.

With that information, a 6 phase, 8 pole unidirectional motor (designated D222 LC#4) was constructed.

Use of an 8 pole motor forces a change in the speed for optimum performance because with a greater number of poles (more magnetic flux) peak efficiency appears at a lower speed and higher torque. Whereas the previous 4 pole motors were designed to operate at approximately 42,500 rpm (the gear ratio of 8.5 times the cruise propeller speed of 5,000 rpm), the new 8 pole motors were designed to operate for peak efficiency at approximately 32,600 rpm for cruise. That speed change required that the propeller design speed be changed (using the same gearbox).

Because of an insufficient quantity of thin 24 slot laminations, the new motor (D222 LC#4) was constructed with standard thickness, 24 slot laminations and with standard potting compound. The thicker laminations and the standard compound were less optimum relative to heat rejection rate and thus the heat rejection rate of the new motor was reduced to 625 watts (compared to 750 watts for the stator of D222 LC#1) at 152 degrees C.

The D222 LC#4 motor (8 pole, 6 phase) was tested using both General Electric and IXYS Corporation transistors. The test with IXYS transistors showed stall torque (for a no load speed of 10,000 rpm) of 700 oz-in a peak efficiency of 83%. That motor (D222 LC#4) was therefore used in the propulsion system that was assembled, tested and finally delivered to the Air Force.

Controller Development

This effort consisted of the controller design and fabrication.

During preliminary studies of speed control for the RPV application, it was learned, through performance tests of a small, existing motor, that the planned speed control method could not provide adequate motor operation at both the cruise and climb conditions. This was an important finding and it caused significant reanalysis and replanning of the methods needed to vary motor performance between the cruise and climb conditions.

Nu-Tech believes that the highest power density power source for the application is a hydrogen/oxygen fuel cell (now under development by Nu-Tech). After finding speed control to be inoperable over such a wide range in power of 5 to 10 hp, Nu-Tech decided to apply the efficient continuous on-time voltage (the originally planned method used an inefficient discrete on and off time of applied voltage) at approximately 150 vdc for cruise operation, and to obtain climb power by also applying the efficient full on-time supplied voltage at approximately 200 vdc. Unfortunately, the fuel cell or any battery system cannot operate at two voltage levels without significant increase in size and weight.

Next it was considered to use a technique of dual winding of the motor. Although this method could be utilized, it was clear that significant, further development is needed to make the technique usable for the RPV application.

The most promising approach to an overall solution rests in accomplishing climb using only a slightly higher power than is used for cruise, perhaps a 10% increase. This power increase can be achieved, without loss in efficiency, by utilizing Nu-Tech's unique speed control technology. Hence not only is motor size and weight minimized, but so too is that of the electronics and battery system. Because of what this offers in improved payload, Nu-Tech decided to discontinue any 10 hp development and to concentrate on testing at the 5 hp condition where efficiency could be optimized.

In regard to the subject of commutation, a high frequency oscillation was encountered on the back EMF signal. The oscillation, or ringing, interfered with motor commutation. Therefore a "protective window" was programmed into the controller by software to prevent the transistors from receiving false signals caused by the ringing. Should the ringing exceed the protective window, the transistors will fail. The software was optimized to provide the widest window without interfering with commutation. A marked improvement in holding the ringing within the window and providing commutation to the required output (5 hp) was facilitated by using a dual winding on the stator and a doubling of transistors within the electronics.

System Configuration and Test

The System Configuration and Test effort included 1) propeller selection and calibration, 2) system assembly, and 3) system testing.

Nu-Tech originally planned to use a propeller that had earlier been obtained from Sensenich Corporation of Lancaster, PA. However, it was found that the propeller could not be used because it could not absorb 5 hp at 5,000 rpm (It would have had to run much faster at that power level.) Nu-Tech therefore obtained a new propeller from the Prince Aircraft Company of Waterville, OH. That propeller, which was white in color and was thus labeled the "white" propeller, was sent to the Southwest Research Institute for modification and calibration. The Southwest Research Institute reduced the tip diameter of the propeller (from the original 30 inches to 21.75 inches) such that the propeller then would absorb 5 hp at 5,000 rpm and 10 hp at 6,300 rpm. This yielded a "calibrated" propeller that could be used in absence of a load dynamometer to judge the output of the motor.

The complete propulsion system, including the motor, controller, gearbox, and white propeller was assembled and subjected to a powered bench test. The voltage applied to the motor was incrementally increased up to 120 vdc which yielded a motor speed of 29,790 rpm and a propeller speed of 3,488 rpm. Using the propeller's power calibration curve, that speed equates to a power of 1.65 hp.

As stated earlier, it was learned that an 8 pole motor would be required for the application. (The white Prince propeller was selected for a 4 pole motor.) With the change from a 4 to 8 pole motor design, it was necessary to change the motor's operating speed to attain optimum performance. Because there was insufficient time to allow a change of gearboxes (a lower ratioed gearbox would have allowed use of the previous propeller speeds, i.e. the white Prince propeller) it was necessary to obtain a new propeller.

The new propeller was also obtained from the Prince Aircraft Company, and it was labeled the "black" propeller because of its color. To allow a reduction in motor speed from 42,500 rpm to 32,600, the black propeller was designed to absorb 5.0 hp at approximately 3,800 rpm. Due to insufficient time, the black propeller was not calibrated.

It was planned to perform all powered testing using an electric dynamometer. However, testing with two different models showed that the devices worked well at speeds up to 10,000 rpm, but that the power data was not accurate at higher speeds. The method of power measurement was therefore broken into two approaches.

At conditions of low speeds, below 10,000 rpm, the power was measured using either the string and pulley method, the dynamometer, or both (as a check). To determine the power for conditions of higher speed, Nu-Tech developed a mathematical calibration procedure which was based upon the principle that motor torque sensitivity (i.e. stall torque per ampere) remains relatively constant over speed. That is, torque is proportional to current. The torque sensitivity was measured by pulley and string methods. That sensitivity was then used to mathematically convert the measured motor currents (at much higher speeds under dynamometer loading) to output torque.

Several years ago, Nu-Tech developed an analytical method of predicting peak efficiency operating conditions for brushless dc motors. That method, which uses end point intercepts of straight line curves, relates no-load speed and stall torque to no-load current and stall current. The method was used to check the results of the above torque sensitivity approach and it was found to closely agree. This correlation gives Nu-Tech high confidence in the method used to convert measured motor current to motor output torque.

The complete propulsion system, including the motor, controller, gearbox, and black propeller was assembled and subjected to a powered bench test. The system was run up to an applied voltage that equalled the limits of the power supply. The power supply was modified to allow a higher voltage and the test was continued until the applied voltage reached 150 vdc. At that condition the measured propeller speed was 4,003 rpm.

Using the mathematical method of converting measured motor current to output motor torque, the motor (not including gear train) power was determined to be 5.12 hp for the 4,003 rpm condition.

An important part of the system testing involved the study of starting the motor under conditions of full battery voltage. For an early, 4 phase motor, starting was actually performed using an inertia load similar to that of a propeller under conditions of an applied full voltage of 150 vdc. However, for the final, 6 phase motor, time did not permit the development of the same capability in that new motor system.

The 6 phase motor was configured to start in the following manner. First, 35 vdc are applied to the motor. Pulse width modulation of the applied voltage is used to prevent an over-current condition which could cause burnout of the transistors. The motor is started utilizing an AC mode of operation. That mode is continued until the motor attains a speed (approximately 1,000 rpm) sufficient to allow the motor to enter a DC mode of operation. Once in the DC mode, the applied voltage is increased to any higher value up to a maximum of 150 vdc at which voltage full power (i.e. 5 hp) is attained. Starting of the 6 phase motor under full battery voltage must be addressed in Phase II.

The Nu-Tech drawing (number 50A002) of the final motor configuration, the one delivered to the Air Force, is included in this report.

RESULTS

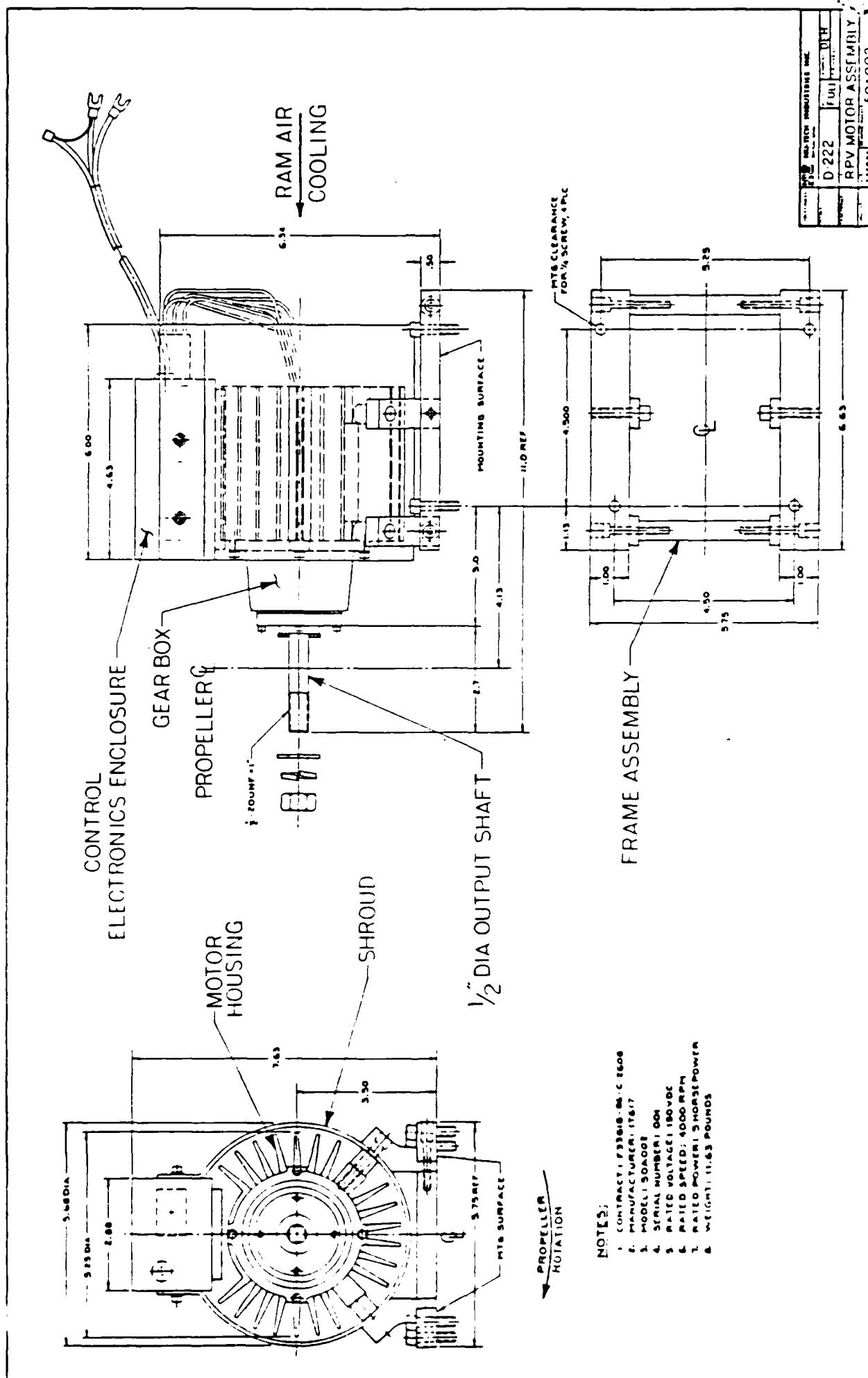
1. A complete electric propulsion system consisting of a brushless dc motor, controller, gearbox, and propeller were configured that has potential as an RPV propulsion system.
2. A light weight, brushless dc motor and companion electronic controller was produced and tested at a power level in excess of 5 hp at a propeller speed of 4,003 rpm. (The gear train output was slightly less than 5 hp.)
3. Heat rejection from the high power density brushless dc motor was tested in the RPV configuration. The results show that improved and adequate cooling should be attainable through concentrated analysis and design of a total cooling system.
4. The motor, controller and heat rejection hardware were packaged for minimum size and weight, and actually weighed much less than the 25 pound target of the original solicitation.

The final Phase I component and system weights are as follow:

Stator	2.42
Rotor & Bearings	0.77
Subtotal	3.19
Fin Housing Assy	3.33
Gear Assy	2.75
Base Assy	1.16
Circuit Board	0.32
Heat Sink	0.84
Subtotal	1.16
Total Weight	11.59 pounds

5. The Phase I goal of proving the feasibility of electric propulsion for RPV applications by demonstrating the performance capability of a brushless dc motor with electronic controller and gear reducer system that is configured for optimum size and weight was attained.

These Phase I results show that continuation of the development effort to Phase II is justified.



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